Active Camouflage of Underwater Assets (ACUA)

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Award Number: N00014-07-1-0842

LONG-TERM GOALS

The long-term goals of this research are to develop the control methodology for active cloaking of underwater assets and the initial hardware concepts to test the proposed cloaking approach. This work is a natural extension of ONR Project N00014-02-1-0211 (Optical Variability and Bottom Classification in Turbid Waters: HyMOM Predictions of the Light Field in Ports and Beneath Ship Hulls) where the perceptibility of underwater assets was modeled.

OBJECTIVES

The initial objective of this work is to extend the existing 3-D Hybrid Marine Optical Model (HyMOM) (Reinersman and Carder 2004; Carder et al, 2005; Carder et al. 2006a and 2006b; Carder et al. 2008;) to determine the three-dimensional light structure of representative marine environments in order to calculate the character of the radiance field needed to remove asset contrast with the background. A secondary objective is to develop a practical method to provide the additional radiance necessary to accomplish this task and to make the asset "self-aware" of its background contrast. Only in this manner will the asset be able to change radiance fields with environmental conditions.

APPROACH

Our approach rests on the foundation of our knowledge of how light interacts with water and the bottom and how it is spectrally and spatially transformed before it can become water-leaving radiance L_u. We will employ two primary mechanisms for actively controlling the cloaking. First, we will use our 3-D Hybrid Marine Optical Model (HyMOM) to understand the spatial structure (e.g. bi-directional reflectance distribution factor) of various natural waters. These results will be used to guide the placement strategy and radiant intensity for light sources employed to disguise underwater objects. Armed with that predictive knowledge, we propose to demonstrate that hybrid, electro-optic "chromatophores", that is, spectral-photophores can be utilized to provide active cloaking. The asset must also "self aware" of its contrast relative to the background. HyMOM will be used to size and

Report Documentation Page						Form Approved OMB No. 0704-0188
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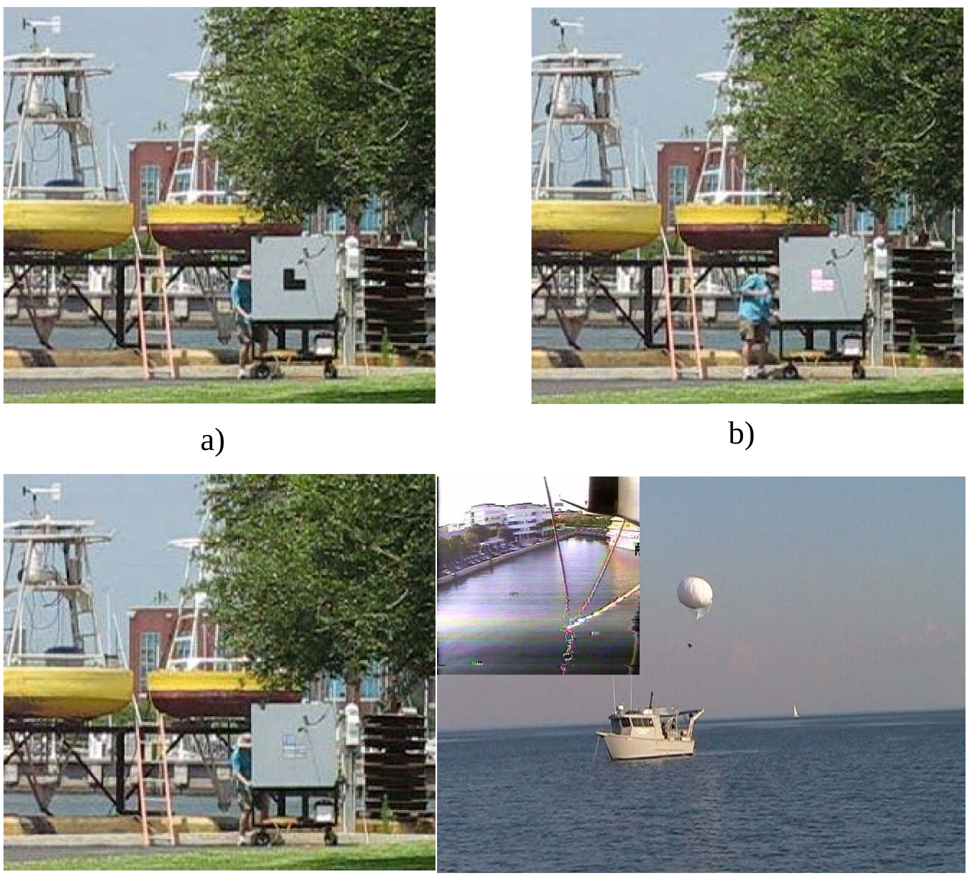
1. REPORT DATE **2009**		2. REPORT TYPE				3. DATES COVERED **00-00-2009 to 00-00-2009**
4. TITLE AND SUBTITLE **Active Camouflage of Underwater Assets (ACUA)**						5a. CONTRACT NUMBER
						5b. GRANT NUMBER
						5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)						5d. PROJECT NUMBER
						5e. TASK NUMBER
						5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of South Florida,College of Marine Science,140 7th Avenue South,St. Petersburg,FL,33701**						8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)						10. SPONSOR/MONITOR'S ACRONYM(S)
						11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT						
15. SUBJECT TERMS						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**		

distribute light sources of the proper angular output to render the asset imperceptible by aircraft sensors.

WORK COMPLETED

The tasks addressed involved modeling the light field about a black underwater vehicle in shallow water, constructing and testing an LED panel to obscure a vehicle, and constructing and testing a control system to match the panel to the background radiance field. The model provided predictions of radiance field and power requirements necessary for obscuring or finding a "vehicle" under various environmental conditions (water depth, vehicle depth, bottom albedo, and water clarity; e.g. Carder et al. 2008). The panel was constructed, water-proofed, and tested sub-aerially, along with the control system. An underwater control system and a second panel consisting of organic light-emitting diodes was also completed. In addition, an aerostat for observing underwater objects was provided by USF and instrumented with digital video and high-definition cameras and navigation and control systems.



a) b)

c) d)

Figure 1. The contrast between a 30% grey panel and the LED panels where LEDs have a) no power and are black; b) full power and are white, and optimal power and have no-low-contrast with background. An aerostat launched from a boat is shown in 1d with an aerial view shown in the inset.

The primary purpose of the control system is to measure and compare color radiance from at least two directions. The ultimate goal was to send instructions to several LED light sources in order to minimize the difference between the LED panel (e.g. upper LED panel in Fig. 1c) and the background). This device was designed to measure several light field and location variables simultaneously, convert the measurements to standard units, and send that information to a PC or other digital device using one or more serial communication lines. The two signals were compared and matched for the upper left LED panel element of Figure 1c. This panel element essentially disappears. Neither of the other two LED panel elements in Fig. 1c used this precise matching system and were more apparent relative to the background. The LED panels and controller are water-proofed and ready for a submarine testing.

Tests of our ability to camouflage an ROV with LED panels over a clear bright bottom with validation provided by the aerostat await future funding opportunities. Two projects were completed, however, as steps in that direction: 1) development of a Simultaneous Multiple Colored Radiance Sampler – Underwater Prototype (SMuCRS-UP), and 2) development of a prototype organic light-emitting diode panel.

SMuCRS-UP was designed to measure the reflected light from an actively camouflaged underwater panel in comparison to light reflected from the adjacent underwater environment. It was designed to measure several light field and location variables simultaneously, convert the measurements to standard units, and send that information to a PC or other digital device using one or more serial communication lines.

Time, location, and orientation information are needed to determine the orientation of the sun relative to the sensor's field of view. The time, latitude, longitude, compass heading, and the radiant color data from multiple sensors is transmitted once a second over a RS232 serial connection for external logging or use. Additional measurements may be needed to fully characterize the light field and in situ optical properties.

The core of the unit is a Parallax[@] Propeller microcontroller containing 8 processing subunits. The existing SMuCRS prototype measures radiant color information from up to 4 TAOS TSL230 color sensors, though only two sensors are presently connected to this device. The microcontroller uses a GPS receiver mounted in one of the sensor housings to provide location and time information. If the GPS unit is unable to receive the satellite information (.e.g. unit is submerged), a time estimate is made by extrapolating from the last GPS time value. The horizontal orientation of the system is determined using a digital compass chip mounted on the microcontroller board.

The controller housing (the metal can in Fig. 2) is configured with 4 electrical connection ports. One of these ports provides power and communication to the controller, while a second provides the connection to a pair of radiance sensors (gray cylinders in Fig. 2). A third port is intended for optional sensors, and/or a second set of radiance sensors. The fourth port is presently configured for higher speed communications and reprogramming the controller. The can is approximately 17 cm long, with a 10cm diameter. Since the dimensions of the controller board is only about 8x10x2 cm, there is room for additional boards and wiring inside the controller housing.

Figure 2. Simultaneous Multiple Colored Radiance Sampler – Underwater Prototype (SMuCRS-UP).

A bifurcated waterproof cable connects the controller housing to two radiance sensor units. Both sensor units contain a TAOS$^{@}$ color sensor, and one also contains a GPS receiver. This cable is about 1.25 meter in length to allow flexibility in orienting the radiance sensors.

The prototype sensor-enclosure design provides the radiance sensors with a nominal 10° field of view (the actual FOV needs to be confirmed since the sensors have been repositioned in the new housings). The individual color sensors respond to visible light (~400 to 1000 nm) and provide estimates of the Red, Green, Blue, and Clear irradiance. These color sensors can operate with irradiance levels as great as ~1100 $\mu W\ cm^{-2}$. The performance of the SMuCRS components was excellent as indicated by the contrast reduction that it provided as shown in Figure 1c.

A low-resolution Organic Light-Emitting Diode (OLED) panel (Fig. 3) was fabricated for underwater use for testing of active camouflage strategies. It was completed and delivered in December 2008, shortly before this contract was completed. While it provides a wide range of hues and tints and could match any laboratory background, its radiant power is inadequate for bright sub-aerial scenes or underwater over shallow, bright bottoms.

For the simple prototype shown, consisting of cell-phone OLED screens with spaced with 2” centers, it is anticipated that the panel can be controlled to match radiance fields with irradiance reflectance values less than about 5% near the surface or at depth. This will blend in with most natural waters (Fig. 3a, b, c) when observed with wide-angle video from aircraft above 200’ altitudes. Tests of the OLED panel, using the SMuCRS-UP to control its upwelling radiance field to match that of the adjacent waters, remains to be accomplished. Future tasks include prototyping mother boards to allow smaller margins (e.g. <0.25”) between screens to allow scene matching for higher-resolution viewing. It also includes creating larger panels with narrower margins.

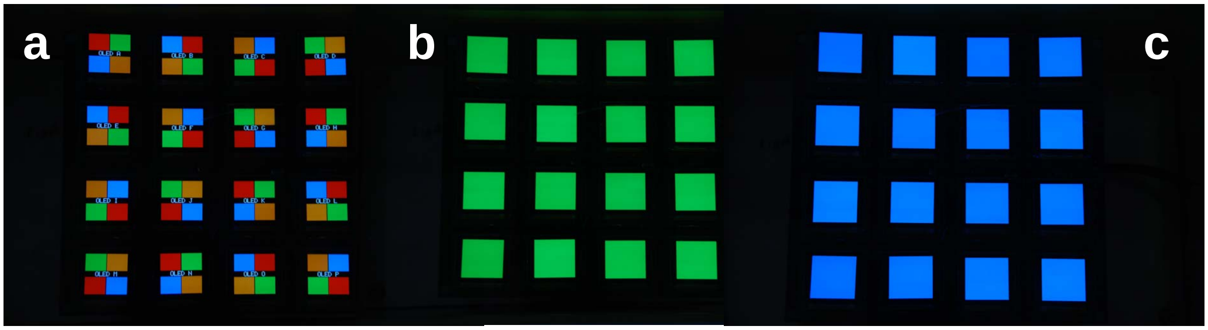


Figure 3. Array of OLED cell-phone screens with 2" centers: examples of a) four basic colors with b) green and c) blue examples simulating hypertrophic and eutrophic waters. Scenes with shallow, sandy bottoms would require more of yellow radiance. Future prototypes will have smaller margins, allowing cloaking even while higher-resolution "searches" are under way.

To prepare for these next steps and to anticipate problems associated with matching natural 3-dimensional light fields, the existing Hybrid Marine Optical Model HyMOM has been extended to better quantify the character of the "cloaking" radiance field necessary to remove contrast between an underwater asset and its background. To better evaluate edge-resolution effects, we have modeled a 2m x 2m x 4m block to which we added combinations of top, side, and extended top lights. The transparent top, to which auxiliary lights are added, overlies the block top. We also have models running for the object at 1.5m and 7.5m depths in 2 more-turbid environments with sea bottoms reflecting either 30% or 15% of incident irradiance.

An example of the effects of "photon wrapping" on model results for this block "vehicle" at 1.5m below the sea surface is shown in the center of Figure 4. Photon wrapping allows a photon to leave, for example, the right side of the cubic model environment and be re-inserted in through the left side at the same angle in order to conserve photons. Photon wrapping is equivalent to modeling an infinite number of identical cubes surrounding the cube of interest. Thus, shadows from a virtual adjacent model cube can be found in the background of the model cube for oblique lighting and observing geometries.

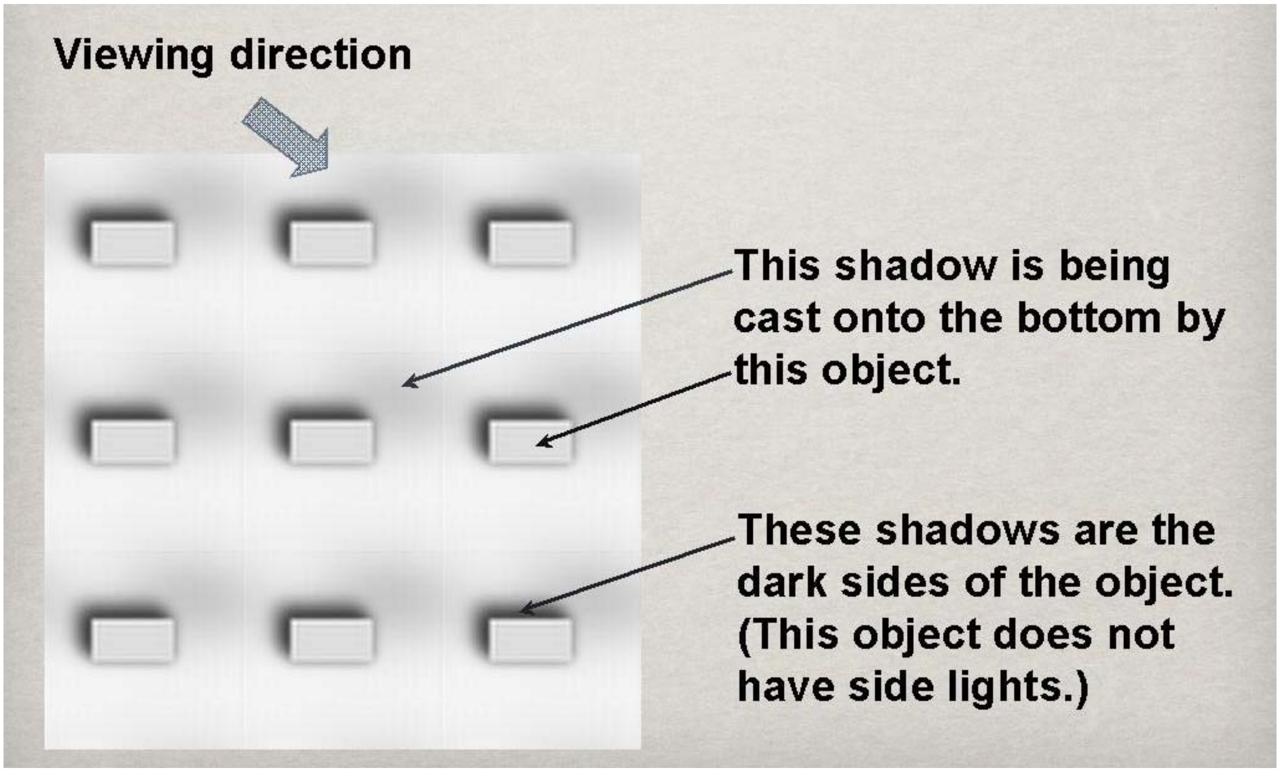


Figure 4. Effects of view angle and photon wrapping are demonstrated.

The center of the nine views in Figure 5 represents the nadir view. The surrounding eight views are views from the eight points of the polar coordinate system. The sun is at an above-surface zenith angle of about 41.25° and a below surface zenith of 29.48° with an azimuth of 3.75°. The projected subsurface views of the sides and shadows on the sea floor at 10m depth are seen for views every 45° of azimuth. A ratio of standard deviation-to-mean (coefficient of variation, CV) for each view is shown to the left of the model images as a measure of the effects of contrast of the block and shadows compared to that of the scene without any objects.

The CV values for views from just below the surface of the black vehicle at 1.5m depth ranged from 0.27 to 0.33 for nadir to westward views, respectively. Views from just above the surface (not shown), produced lower CV values, from 0.25 to 0.29. The surface radiance appropriate for air searches includes reflected skylight, but a best-viewing case is shown with no waves, clouds, nor sun glint.

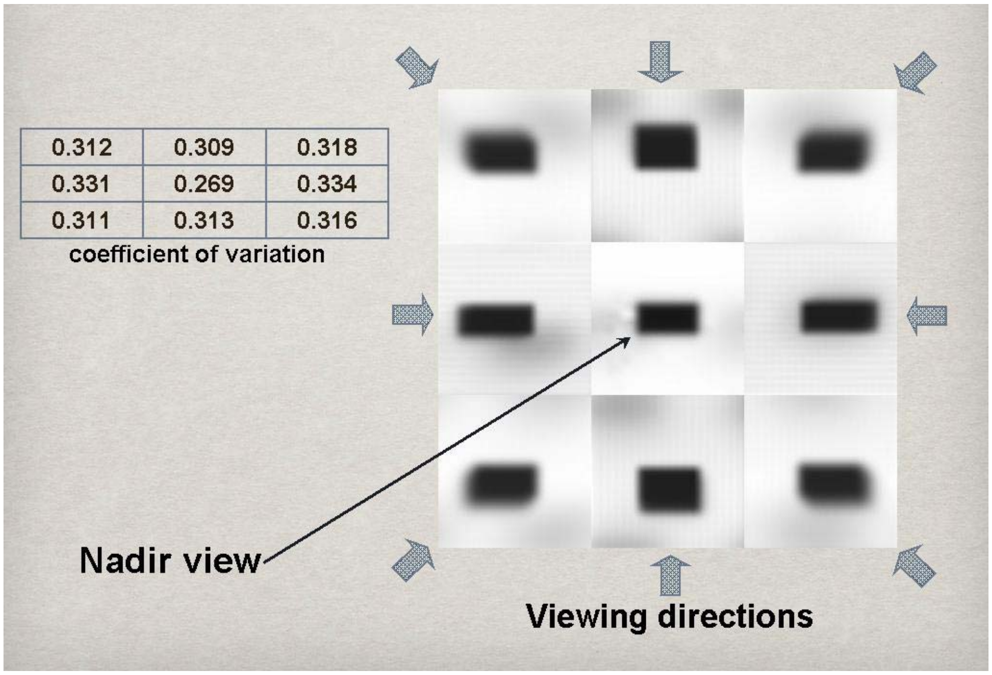


Figure 5. ***Example of the effects of viewing angle on model images of a black vehicle of 2m vertical thickness at 1.5 m depth over a bright bottom at 10m depth. CV values for each of nine views are shown in the matrix box: nadir (center) and eight azimuthal views every 45^o.***

Figure 6 demonstrates the resulting contrasts when modeling an array of lights covering only the top of the black vehicle, and an array of lights fixed on the vehicle top and sides. Clearly, the addition of top lights and side lights makes a tremendous difference in the obscuration or “cloaking” of a submersible. A five-fold and a two-fold reduction in nadir-view and oblique-view CV values, respectively, result from optimal addition of top lights. However, six-fold and four-fold reductions in nadir-view and oblique-view CV values, respectively, result from optimal addition of top and side lights. For the vehicle at 7.5m depth with top and side lights, contrast CV is almost two times the near-surfaces values due to shadow effects (not shown). The mean CV is 6% at 1.5 m but increases to 11% at 7.5 m. Addition of wave effects and sun glint or cloud reflection will make the vehicle virtually impossible to detect only 1.5 m below the surface for observational systems of >2.5 cm resolution limits.

RESULTS

A sub-aerial, active-camouflage system has been demonstrated, and it is ready for submarine testing. It has a contrast-elimination module that controls the radiant power emanating from LED or OLED panels. Submerged, cloaking-panel tests with an existing aerostat viewing a camouflaged ROV await future funding.

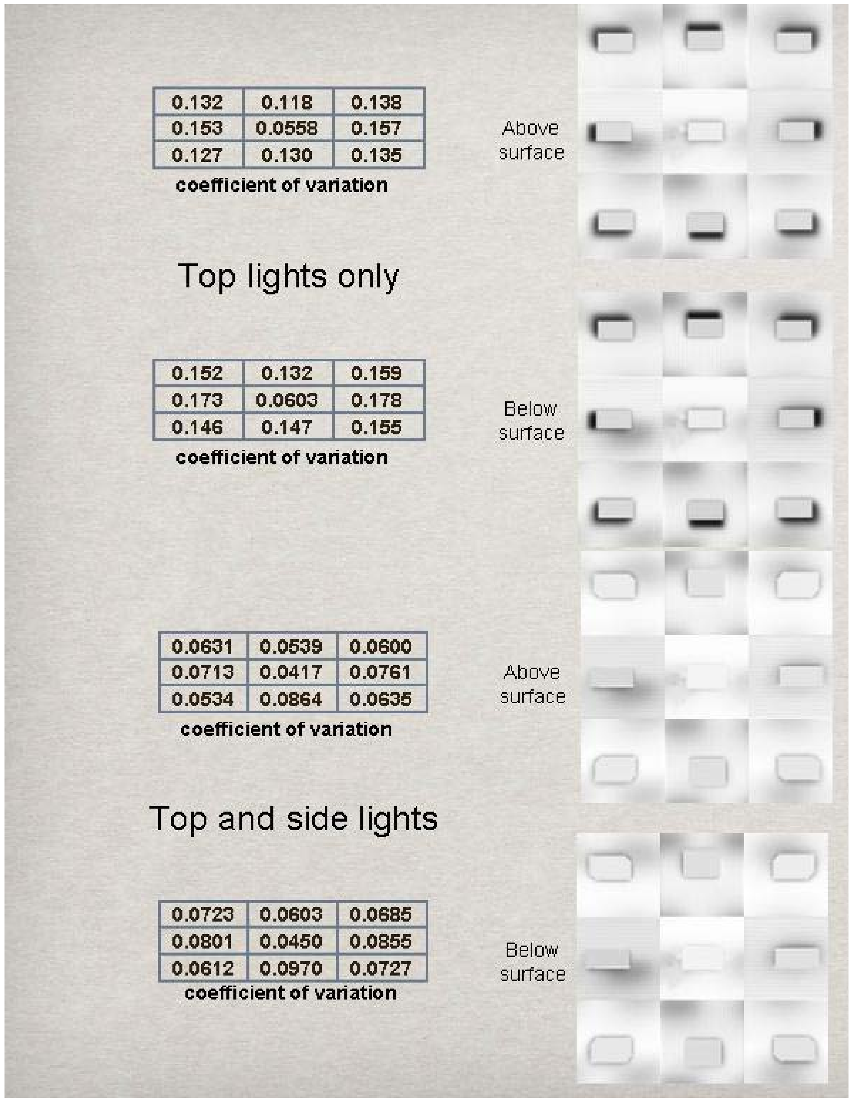


Figure 6. Contrast-stretched results with arrays of top lights and top plus side lights. Note that much of the scene variation in shallow waters is due to object shadows

The power and angular distribution requirements for radiance from cloaking LEDs for a variety of shallow-water settings have been determined using 3-D HyMOM model runs. Simulations of near-surface, actively camouflaged objects result in much smaller bottom-shadow effects and less contrast for clear waters than for simulations of near-bottom, camouflaged vehicles. Coefficients of variation of as small as 4% have been achieved for pixels in a scene with a 1.5m deep, actively camouflaged vehicles over a 10m "bright-sand" bottom. CV values for the un-camouflaged black vehicles were as high as 33% depending upon lighting and viewing geometries. The most expensive scenario in terms of power to operate an active camouflage system results from near-bottom deployments where shadows of the object on the bottom must be artificially in-filled to achieve effective camouflage. In this case the LED radiant flux onto the bottom must match that of down-welling sunlight, an expensive proposition.

IMPACTS/APPLICATIONS

The Hybrid Marine Optical Model has been applied to evaluating the 3-D light field beneath ships, around pilings, around mine-like objects, and around AUVs at various depths. It has also been used to prescribe the active light field necessary to "cloak" underwater assets from daylight observation by aircraft or sub-surface observations. These results can be used to impact search strategies for underwater mines, AUVs, and mini-submarines, and to guide the application of active camouflage to "cloak" U.S. underwater assets. An underwater OLED "cloaking" panel and control hardware have been developed for testing the effectiveness of various underwater cloaking strategies.

RELATED PROJECTS

- USF College of Marine Science Center for Underwater Observability and Optical Communication: Kendall L. Carder and David K. Costello, P.I.s. This project provided the boat, ROV, and aerostat with associated instrumentation to initialize HyMOM model runs and validate the effectiveness of various cloaking approaches.

- SRI International: John Bumgarner and Eric Kaltenbacher are providing MEMs-based panels as a subcontract to USF.

- Optical data sets for coastal Florida and Bahamas waters (see references) were collected by various past ONR and NASA projects of K.L. Carder, especially ONR project N00014-02-1-0211 (Carder and Reinersman), which has transitioned into ACUA. Studies in modeling and measuring seawater optical properties were funded by ONR #N000140-02-1-0211 "Optical Variability and Bottom Classification in Turbid Waters: Phase II" and #N00014-03-1-0177 "Distribution of our CoBOP Results: IOPs and Albedo Spectra for Incorporation into Radiative Transfer Models." Ambient light condition modeling was funding by ONR #N00014-03-1-0625 "A Hybrid Modular Optical Model to Predict 2-D and 3-D Environments in Ports and Beneath Ship Hulls for AUV Sensor-Performance Optimization in MCM Activities."

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Provisional Patent Application USF Ref. No.: 07A063PR (July 24, 2007) for Reinersman, Carder, and Costello for *Monochromatic Contrast Reduction of Objects.*

U.S. Patent 7,286,214 B2 (October 23, 2007) by USF for Phillip N. Reinersman and Kendall L. Carder for *Method and Program Product for Determining a Radiance Field in an Optical Environment*.